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Reading spectrometric information in the diffraction spectral devices of the optical range

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ABSTRACT

The problems of the formation and output of the measurement results of the energy spectrum of the optical signal in a spectrum analysis system based on a device with a diffraction grating and fiber-optic transmission system (FOTS) of the analyzed signals are considered. The use of FOTS allows implementing a contactless method of spectrum analysis. A mathematical model has been developed for obtaining reference values of the energy spectrum by linear CCD sensor detection. A method for correction reading results allows us to take into account the nonuniformity of the spectral sensitivity of the linear CCD sensor, the frequency response of the attenuation of the optical fiber, and also the features of the formed spectra in different diffraction orders is proposed.

Keywords: spectral analysis system, optical radiation, diffraction grating, linear CCD sensor, spectrum reading, energy spectrum, optical fiber, contactless method.

1. INTRODUCTION

The importance of developing modern optical systems for spectral research is have been supporting by their wide application\(^1\), and the course of which processes are accompanied by the emission of electromagnetic radiation in a wide frequency range, including optical. The methods of optical spectroscopy have various important advantages compared with other research methods, which include: real-time analysis, high density and transfer speed of information, and the ability not to demolish the conditions of the process. Improving the metrological characteristics of the technical means of optical spectroscopy is impossible without the further development of the spectral measurements theory, where the main task is to point a relationship between the physical spectrum, which recorded using the equipment and the mathematical spectrum, which is the Fourier transform of the signal\(^2\) (relationship input-output of spectral device), which implies improvement of the mathematical model, which allows one to describe the acquisition of apparatus spectrum in systems spectrum analysis. The diffraction spectral devices need to develop mathematical models for describing spectrum information and the reading process of spectroscopic information in these devices. Most often, such models based on geometric optics methods and some heuristic statements\(^3\),\(^4\), which result in a transition from radiation, presented in the form of rays to the transmission of diffracted light intensity at the output of the spectral device. This approach does not allow us to solve the main problem of the spectral measurements’ theory noted above.

This requires further development, especially because the properties of the signal cannot be attributed to the beam, and the energy spectrum receipt should be considered.

An alternative approach to the description of the spectral conversion realized in a diffraction device was proposed. And also, was shown the first receipt of the complex, and then the energy spectrum of the analyzed optical signal\(^5\). The principles of radio optics\(^6\), signal theory\(^7\), and the theory of linear systems\(^8\) are based on a proposed mathematical model. The basis of a sequential description of optical signal conversion by all spectral device elements is also is base on.

A mathematical description is given of the process of obtaining reference for the energy spectrum values when reading spectrometric information using the linear CCD sensor is based on the developed model. Besides, the problems of reading results correction, due to the need to take into account the non-uniformity of the spectral sensitivity of the linear CCD sensor, the attenuation characteristics of the optical fiber, as well as the features of the formed spectra in different diffraction orders, are considered.
2. FORMATTING AND READING THE OPTICAL SPECTRUM

Figure 1 shows the optical diagram of the spectrum analysis system, which is the device with the diffraction grating, and the FOTS. The system consists of a sequentially located FOTS, a system of forming lenses, a diffraction grating, and an optical coherent Fourier processor with a placed device in the back of the focal plane of the lens be the spectrum device is located, which is based on the linear CCD sensor.

\[ S \rightarrow \text{Source of radiation} \rightarrow \text{FO} \rightarrow \text{Lens} \rightarrow \text{Diffraction grating} \rightarrow \text{Optical Coherent Fourier Processor} \rightarrow \text{Linear-CCD} \rightarrow \text{Registrar} \]

- **S** – the source of radiation, **FO** - the lens forming system, **F** - the focal length of lenses, **D** - the size of the diffraction grating aperture

Figure 1. The optical schematic of the spectrum analysis system, which consists of the device with a diffraction grating, and the FOTS.

The FOTS includes an optical system designed for efficient input of the analyzed optical radiation into the fiber, the optical cable, and the output system.

The front of the wave emerging from the system of the output radiation in the case of radiation transmission via FOTS turns out to be different from the required uniform and planar one, which is the forming optics system is corrected. And then the radiation is fed to the diffraction grating.

The FOTS use allows implementing a non-contact spectrum analysis method, which allows research of the physical and technological processes, which take place in extreme conditions (extreme temperature, dangerous chemical environment, etc.). In this case, the influence of extreme conditions directs only on the radiation input system into the fiber, which imposes strict requirements on its resistance to these effects. In the same case, the spectral device could be removed at a distance, which is measured in kilometers from the object.

The mathematical model based on the principles of radio optics and the theory of linear systems describes the energy spectrum obtaining solution by an analysis system. And that model obtained by sequentially considering the optical radiation conversion from the input of the device aperture to the reading spectrometric information result.

An exhaustive characteristic of any linear system is its apparatus function. According to the general principles of the linear systems theory, the apparatus function as a result of the conversion of a monochromatic homogeneous electromagnetic plane by the device could be obtained.

In, it was shown the input-output coupling of a spectral device as the result of an integral transformation could be written.
where $S_n(\omega, t)$ is the apparatus spectrum. $S(\omega')$ is the real spectrum, i.e. mathematical, $\Delta \Omega$ is the band of analyzed frequencies, and the core of this solution is a complex apparatus function, which for a spectral device with a diffraction grating could be defined in the form of:

$$K(\omega, \omega', t) = \hat{E} \exp\left(\iota \omega'[t - z / c]\right) \sum_{k=\infty}^{\infty} C_k \sin\left(\frac{(\omega_t(x) - \omega') T_a(x)}{2}\right),$$

(2)

where $\hat{E}$, $\omega'$ are the complex amplitude and frequency of the monochromatic homogeneous electromagnetic plane wave input, $k'$ is the wavenumber, $z$ is the coordinate along which the wave propagates, $k$ is the diffraction order number, $c$ is speed of light, $C_k$ are the expansion coefficients of the transmission function of the diffraction grating in the form of expansion Fourier series at the aperture, $T_a(x) = Dx / 2cF$.

At the same time, the connection of spectral frequency and spatial coordinates in the back of the focal plane of the lens as an expression:

$$\omega_t(x) = \frac{k \Omega_g cF}{x},$$

(3)

where $\Omega_g = 2\pi / T_g$, $T_g$ is the grating period.

Figure 2 shows the model of multi-elemental photo receiver – linear CCD sensor, which accomplishes the reading of spectrometric information in modern spectrum analysis devices.

Each element of the linear CCD sensor accomplishes frequency filtration (in cases of spectral frequencies) in $\Delta \omega_n$ the bandwidth equal to:

$$\Delta \omega_n = \frac{\Delta x_n T_g \omega_n^2}{k \pi c F},$$

(4)

defined by both the parameters of the optical elements of the analysis system and the size of the linear CCD sensor pixel.

In the expression (4) $\omega_n$ is the spectral frequency at the central coordinate of the current pixel. The expression (4) as the highest achievable resolution of the analysis system could be interpreted.

Figure 3 shows the computer simulation result of the resolution change $\Delta \omega_n$ of analysis system by the length of the linear CCD sensor (3,800 pixels) for the following system parameters: $F=25$ cm, $T_g=5$ um, $\Delta x_0 = 3.5$ cm.
Each element of the linear CCD sensor carries out a quadratic detection and temporary integration operation ($T_R$). For each pixel of the linear CCD sensor at a normal (perpendicular plane of the sensitive surface) wave input, it is possible to express the value of the photocurrent in the form of expression:

$$i_n = \gamma q_e \frac{\sqrt{\mu/\varepsilon}}{\hbar \omega} |E|^2 \Delta S_n,$$

where $\varepsilon$, $\mu$ are the dielectric and magnetic permeabilities, respectively, $\gamma$ is the quantum efficiency, $\hbar$ is the Planck constant, $\Delta S_n = \Delta x_n l$, $\Delta x_n l$ are the lengths of the $n^{th}$ element of the linear CCD sensor along the $\omega$ spatial frequency axis, and in the perpendicular direction, $E$ is the optical field electric field vector complex spectrum radiation.

In the case of reading spectrometric information, spectral device functioning with a diffraction grating is consider in the $+1$-diffraction order.

Substitution instead of vector $E$ values of the optical signal, presented in the form of a complex apparatus spectrum, as well as performing operations of spatial and temporal integration, allows presenting the result of photodetection in the form of:

$$\tilde{T}_n = B \int_{\omega_n - \Delta \omega_n}^{\omega_n + \Delta \omega_n} \sin^2 \left[ \left( \omega_n(x) - \omega' \right) T_n l \right] \frac{T_n l}{2} G(\omega') d\omega' = B \int_{\omega_n - \Delta \omega_n}^{\omega_n + \Delta \omega_n} \text{sinc}^2(\cdot) \cdot G(\omega') d\omega',$$

where $B$ is a proportional coefficient, that takes into account factors such as quantum efficiency, etc.

The resulting expression for the photocurrent in each element of the linear CCD sensor allows to define a mathematical expression describing the connection of the input-output of the spectral device in a matrix form for the energy spectrum for detecting the spectrum on all elements:

$$\|G(\omega_n)\| = B \int_{\omega_n - \Delta \omega_n}^{\omega_n + \Delta \omega_n} \text{diag} \{A_n(\omega, \omega')\} \|G(\omega')\| d\omega'.$$

Figure 3. Changing the resolution of the analysis system along the length of the linear CCD sensor.
where \( G(\omega') \) is \( \omega' \) the energy spectrum of the analyzed signal; \( \text{diag} \left\{ A_\omega(\omega, \omega') \right\} \) is the energy apparatus function in a matrix form of a spectral device with a diffraction grating: \( A_\omega(\omega, \omega') = \text{sinc}^2(\cdot) \).

Thus, the reading result of spectrometric information is given in the form of energy spectrum sampled values, averaged by the size of the linear CCD sensor sensitive element and the time of integration of \( T_R \).

3. SPECTRUM RESULTS CORRECTION

Obtained results in the first section show that the frequency scale changes nonlinearly in the case of reading spectroscopic information, while the reading results are reproduced pixel by pixel (linearly).

This fact shows that the spectrum measurement is distorted, which requires input correction.

That the sensitivity of the linear CCD sensor is uneven over the entire analyzing frequencies range should also be noted. Therefore, to calculate the recorded intensity values in each pixel, an additional multiplication of these values by an amount, inverse to the sensitivity value at this wavelength (frequency) is required.

Figure 4 shows the spectral sensitivity presented by the manufacturer in the form of a graph of the Toshiba TCD1304 linear CCD sensor, which is most often used in spectrum reading devices.

This dependency was subjected to approximation. The least-squares method was chosen as the approximating method to obtain an analytical function that describes this dependency.

![Spectral response of CCD](image)

The analytical form of the approximating function depending on \( \lambda \) (nm) has the form:

\[
W(\lambda) = -9.238 \cdot 10^{-6} \lambda^2 + 0.01009 \cdot \lambda - 1.762 .
\]  

Thus, the correction results procedure of spectrum reading is as follows:

1. The conversion of the spatial scale into a frequency one following the expression (4). Transferring the frequency scale to the wavelength scale for the convenient spectrum display if it is necessary.
2. Dividing the reading values array of the linear CCD sensor by the values of its spectral sensitivity calculated by expression (8) - correction of distortions caused by the spectral sensitivity unevenness.

3. Correction of the frequency response of the attenuation used in the optical fiber analysis system.

4. Display the result of spectroscopic measurements and corrections in the form of a relation of the intensity $I$ on the wavelength.

Figure 5 shows the result of the spectrum measurement of the Ocean Optics LS-1 broadband lamp, and the adjusted result according to the algorithm proposed above for the range 400 - 750 nm.

![Figure 5. The correction result of spectroscopy measurements.](image)

It is important to note that in the spectrum analysis of sufficiently broadband radiation sources, the correction is important because it significantly affects the displaying result of the energy spectrum as an energy transmission over frequencies (wavelengths).

**CONCLUSION**

A new mathematical model of the spectral conversion realized in a spectral device with a diffraction grating as part of the further development of the spectral measurements theory in the optical range is purposed, which model consists of the sequential consideration of the optical signal conversion from the input aperture to the result of reading spectrometric information. Based on this model, complex functions and energy apparatus functions, which are its comprehensive characteristics and defined the input-output communication of the spectral device is defined. The issues of reading spectrometric information using the linear CCD sensor are considered. A criterion for determining the system resolution is proposed, which is depending on both parameters of the linear CCD sensor, and the parameters of the optical system. The features of the formed spectra in various orders lead to the need for “pixel-by-pixel” correction of reading results. For this, a technique for processing and correcting the optical spectrum results of reading is proposed.

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